Preprint
UCRL-JC-142223-REV-1

The National Ignition Facility: Status and Plans for Laser Fusion and High-Energy-Density Experimental Studies

E. I. Moses

This article was submitted to
19th Institute of Electrical and Electronics Engineers/Nuclear & Plasma Sciences Society Symposium on Fusion Engineering, Atlantic City, NJ, January 22-25, 2002

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

January 11, 2002

This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

The National Ignition Facility: Status and Plans for Laser Fusion and High-Energy-Density Experimental Studies

Edward I. Moses, *Lawrence Livermore National Laboratory*

***Abstract*-- The National Ignition Facility (NIF), currently under construction at the University of California's Lawrence Livermore National Laboratory is a $2.25B stadium-sized facility containing a 192-beam, 1.8-Megajoule, 500-Terawatt, 351-nm laser system. NIF is being built by the National Nuclear Security Agency and when completed will be the world's largest laser system, providing a national center to study inertial confinement fusion and the physics of extreme energy densities and pressures. In NIF up to 192 energetic laser beams will compress small fusion targets to conditions where they will ignite and burn, liberating more energy than is required to initiate the fusion reactions. NIF experiments will allow the study of physical processes at temperatures approaching 100 million K and 100 billion times atmospheric pressure. These conditions exist naturally only in the interior of stars and in nuclear weapons explosions. In the course of designing the world's most energetic laser system, a number of significant technology breakthroughs have been achieved. Research is also underway to develop a shorter pulse capability on NIF for high power applications. We discuss here the technology challenges and solutions that have made NIF possible along with enhancements to NIF's design that could lead to exawatt power levels.**

I. Introduction

THE National Ignition Facility (NIF) under construction at the Lawrence Livermore National Laboratory (LLNL) will be a U. S. Department of Energy and National Nuclear Security Administration (NNSA) national center to study inertial confinement fusion and the physics of extreme energy densities and pressures. It will be a vital part of the NNSA Stockpile Stewardship Program (SSP), which ensures the reliability and safety of U. S. nuclear weapons without full scale underground nuclear testing. The SSP will achieve this through a combination of above ground test facilities and powerful computer simulations using NNSA's Accelerated Scientific Computing Initiative (ASCI). In NIF up to 192 extremely powerful laser beams will compress small fusion targets to conditions where they will ignite and burn, liberating more energy than is required to initiate the fusion reactions. NIF experiments will allow the study of physical processes at temperatures approaching 100 million K and 100 billion times atmospheric pressure. These conditions exist naturally only in the interior of stars and in nuclear weapons explosions.

II. A Description of NIF

The National Ignition Facility is shown schematically in Figure 1. NIF consists of four main elements: a laser system and optical components; the target chamber and its experimental systems; an environmentally controlled building housing the laser system and target area; and an integrated computer control system.

NIF's laser system, the heart of the facility, features 192 high-power laser beams. Together, the laser beams will produce 1.8 million joules (approximately 500 trillion watts of power for 3 nanoseconds) of laser energy in the near-ultraviolet (351 nanometer wavelength). This can be compared with the energy that was available in the Nova laser, which was operated at LLNL between 1983 and 1999. Nova was configured with 10 laser beams, each of which produced approximately 4.5 kilojoules of energy. Currently the largest operating laser is the Omega Laser at the University of Rochester's Laboratory for Laser Energetics. Omega consists of 60 laser beams delivering a total of 40 kilojoules of energy. Figure 2 schematically shows one of the 192 laser beams, detailing the key technologies that make NIF possible. A NIF laser beam begins with a very modest nanojoule energy pulse from the master oscillator, a diode pumped fiber laser system that can provide a variety pulse shape suitable for a wide range of experiments, from complex high contrast pulses for ICF implosions to high energy extended pulses for weapons effects experiments. The master oscillator pulse is shaped in time and smoothed in intensity and then transported to preamplifier modules (PAMs) for amplification and beam shaping. Each PAM first amplifies the pulse by a factor of one million (to a millijoule) and then boosts the pulse once again, this time to a maximum of 22 joules, by passing the beam four times through a flashlamp-pumped amplifier. There are a total of 48 PAMs on NIF, each feeding a "quad" of four laser beams.

From the PAM the laser beam next enters the main laser system, which consists of two large amplifier units – the power amplifier and the main amplifier. These amplifier systems are designed to efficiently amplify the nominal one joule input pulse from the PAM to the required power and energy, maintaining the input beam's spatial, spectral, and temporal characteristics. The amplifiers, with 16 glass slabs per beam, are arranged with 11 slabs in the main amplifier section and five slabs in the power amplifier section. Together these amplifiers provide 99.9% of NIF's power and energy. The amplifiers use 42 kilogram slabs, 46 cm x 81 cm x 3.4 cm, of neodymium-doped phosphate glass set vertically on edge at

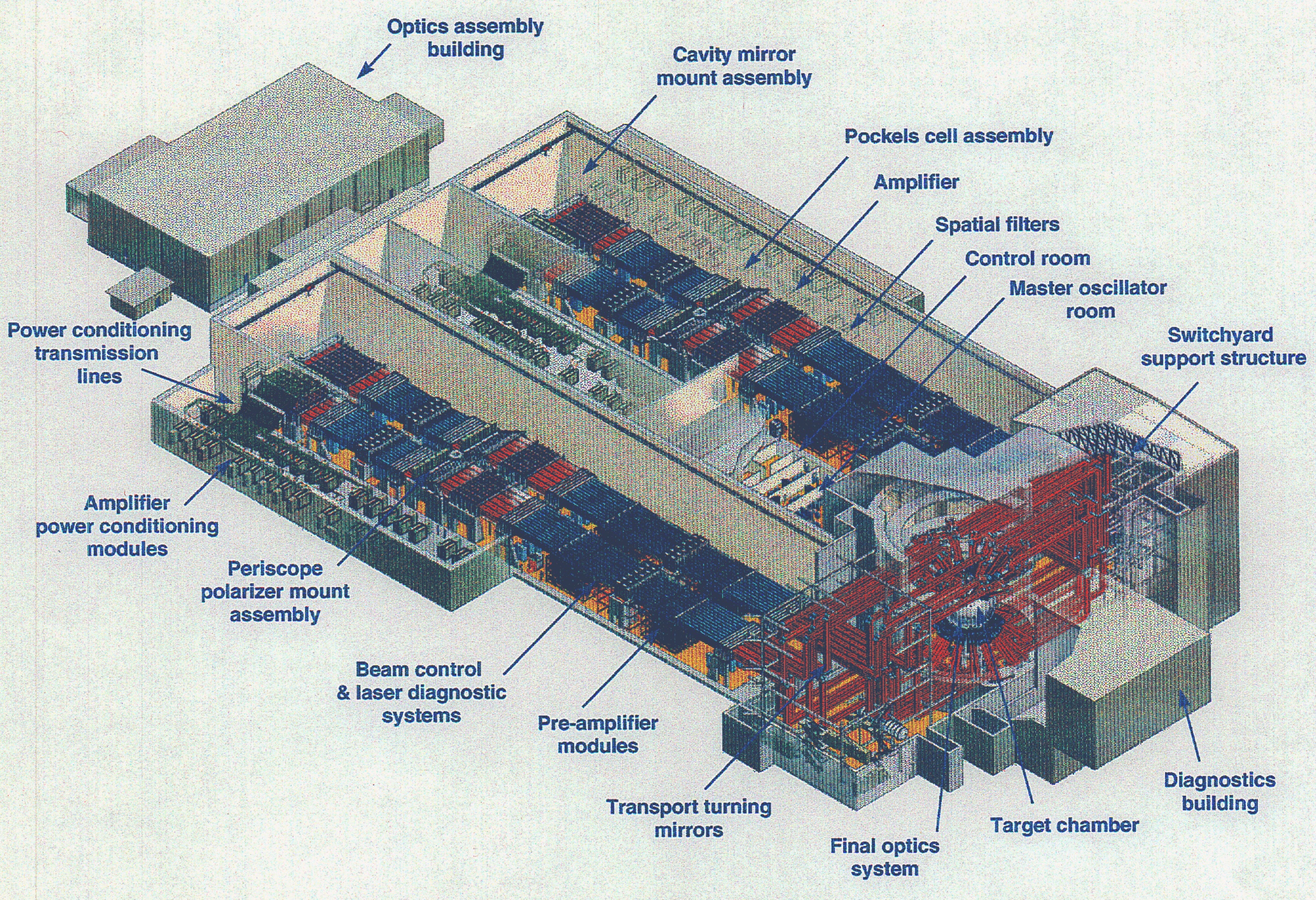

Fig. 1. Schematic view of the National Ignition Facility showing the main elements of the laser system. The 10-meter diameter target chamber sets the scale for the facility.

Brewster's angle to minimize reflective losses in the laser beam. The slabs are stacked four high and two wide to accommodate a "bundle" of eight laser beams (Figure 3).

The slabs are surrounded by vertical arrays of flashlamps, measuring 180 cm in length. A total of 7600 flashlamps and 3072 glass slabs are required for NIF's 192 laser beams. Each flashlamp is driven by 30,000 joules of electrical energy. The intense white light from the flashlamps excites the neodymium in the laser slabs to provide optical gain at the primary infrared wavelength of the laser. Some of the energy stored in the neodymium is released when the laser beam passes through the slab. Advances in glass amplifier technology allow NIF to operate with less than twice the number of flashlamps than Nova even though the laser system will produce 60 times more output energy. The flashlamps will be cooled between shots along with the amplifier slabs using nitrogen gas. NIF will be able to shoot once every 8 hours and a shot rate enhancement program funded by our collaborators from the United Kingdom is working to increase the cooling rate so that NIF can be fired once every four hours.

The NIF amplifiers receive their power from the Power Conditioning System (PCS), which consists of the highest energy array of electrical capacitors ever assembled. The system's design is a collaboration between Sandia National Laboratories in Albuquerque, LLNL, and industry. The PCS will occupy four capacitor bays adjacent to each laser bay as shown in Figure 1.

Each PCS module is configured with eight, 20-capacitor modules delivering 1.7 megajoules per module that power the flashlamps for one beam. The system must deliver over 300 million joules of electrical energy to the flashlamp assemblies in each laser beam. The NIF PCS delivers electrical energy nearly 10 times cheaper per joule than on Nova. Recent tests on a prototype PCS and flashlamp system have now fired over 10000 times at a rate of 1200 shots per month, corresponding to nearly half of NIF's project 30-year lifetime.

A key component in the laser chain is an optical switch called a plasma-electrode Pockels cell (PEPC), which allows the beam to pass four times through the main amplifier cavity. This device uses electrically induced changes in the refractive index of an electro-optic crystal, made of potassium dihydrogen phosphate (KDP). When combined with a polarizer, the PEPC allows light to pass through or reflect off the polarizer. The PEPC will essentially trap the laser light between two mirrors as it makes four one-way passes through the main amplifier system before being switched out to continue its way to the target chamber. The PEPC consists of thin KDP plates sandwiched between two gas-discharge plasmas that are so tenuous

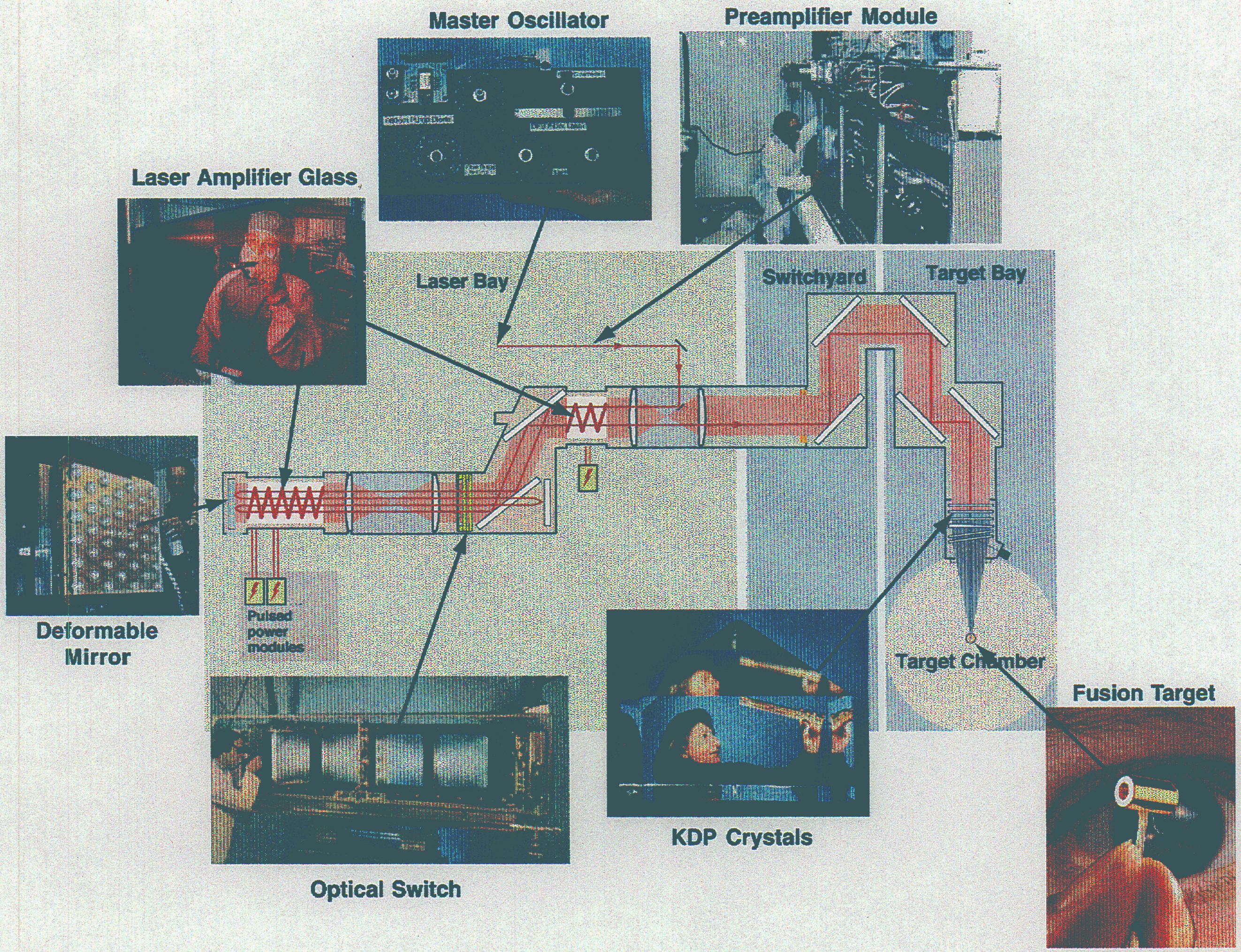

Fig. 2. Schematic representation of a NIF laser beam line highlighting some of the key technology developments.

they have no effect on the laser beam passing through the cell. Nonetheless, the plasmas serve as conducting electrodes, allowing the entire surface of the thin crystal plate to charge electrically in about 100 nanoseconds so the entire beam can be switched efficiently. Figure 2 shows a prototype four-cell PEPC (optical switch) that will be stacked vertically in a single unit.

There are many other parts of NIF that are not covered in detail here. All major laser components are assembled in clean, pre-aligned modules called line-replaceable units or LRUs. These LRUs contain laser optics, mirrors, lenses, and hardware such as pinhole filters assemblies. All LRUs are designed to be installed into NIF's beampath infrastructure system, the exoskeleton of NIF, while maintaining the high level of cleanliness required for proper laser operation. Our industrial partner, Jacobs Facilities, Inc. is responsible for the installation, integration, and commissioning of the beampath infrastructure, which will ensure that the laser maintains the required cleanliness levels throughout the installation and startup phases of the Project.

The NIF target area consists of the 10-meter diameter high-vacuum target chamber shown in Figure 4. The target chamber contains a large number of laser entry ports as well as nearly 200 ports for diagnostic instrumentation and target insertion. Each laser entry port allows a quad of laser beams to be focused to the center of the target chamber through a final optics assembly (FOA). The FOA is a precision optical assembly containing beam smoothing gratings, additional KDP and deuterated KDP plates for second and third harmonic generation to convert the infrared laser light into the ultraviolet, the final focus lens, debris shields and vacuum gate valve for each beam.

The NIF target chamber and final focusing system has been designed with maximum flexibility for experimental users. During initial operation, NIF is configured to operate in the "indirect drive" configuration, which directs half the laser beams into two cones in the upper and lower hemispheres of the target chamber. This configuration is optimized for illuminating fusion capsule mounted inside cylindrical hohlraums using x-rays generated from the hot walls of the hohlraum to

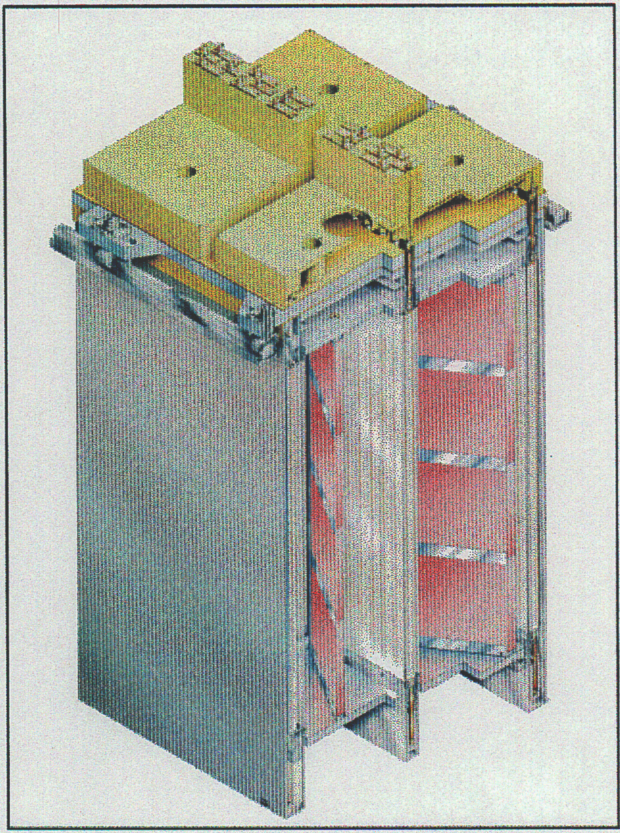

Fig. 3. The photograph on the left shows a laser amplifier glass slab line-replaceable unit assembled in the NIF Class-100 Optics Assembly Building. Laser glass slab LRUs are assembled into amplifier housings that also contain flashlamps used to pump the glass, shown in a CAD rendering on the right.

indirectly implode the capsule. NIF can also be configured in a "direct drive" arrangement of beams, by moving some quads of beams from the upper and lower hemispheres into a more symmetric arrangement of beams. Direct drive ignition requires better energy and power balance between laser beams and better beam smoothing and focusing but the simpler geometry makes direct drive inertial confinement fusion more attractive for ultimately producing a viable power production plant.

III. NIF Project Status

NIF is currently over four years into its construction. Figure 5 shows a recent aerial photograph of the NIF site. The conventional building construction was completed in September, 2001. The 8,000 square foot class-100 clean room Optics Assembly Building is undergoing commissioning of LRU assembly, handling, and transport equipment. Both large laser bays are operating under class-100,000 clean room protocols. Over 1500 tons of beampath infrastructure have now been installed in the laser bays and in October 2001 the first 48-beam clean infrastructure was completed. Also during this time the first laser light from NIF's master oscillator was generated in the fully operational master oscillator room located in the central core of the NIF building. The NIF Project is now entering

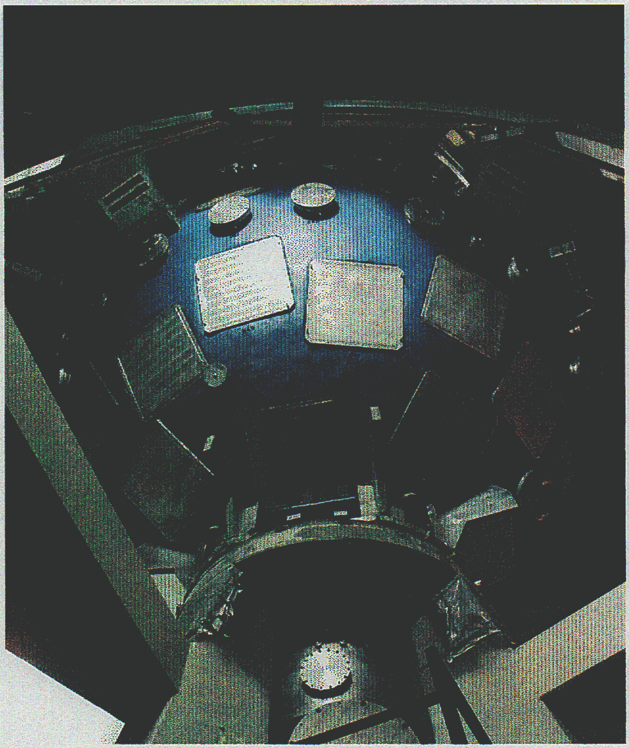

Figure 4. NIF's 10-meter diameter target chamber mounted in the target bay and viewed from below.

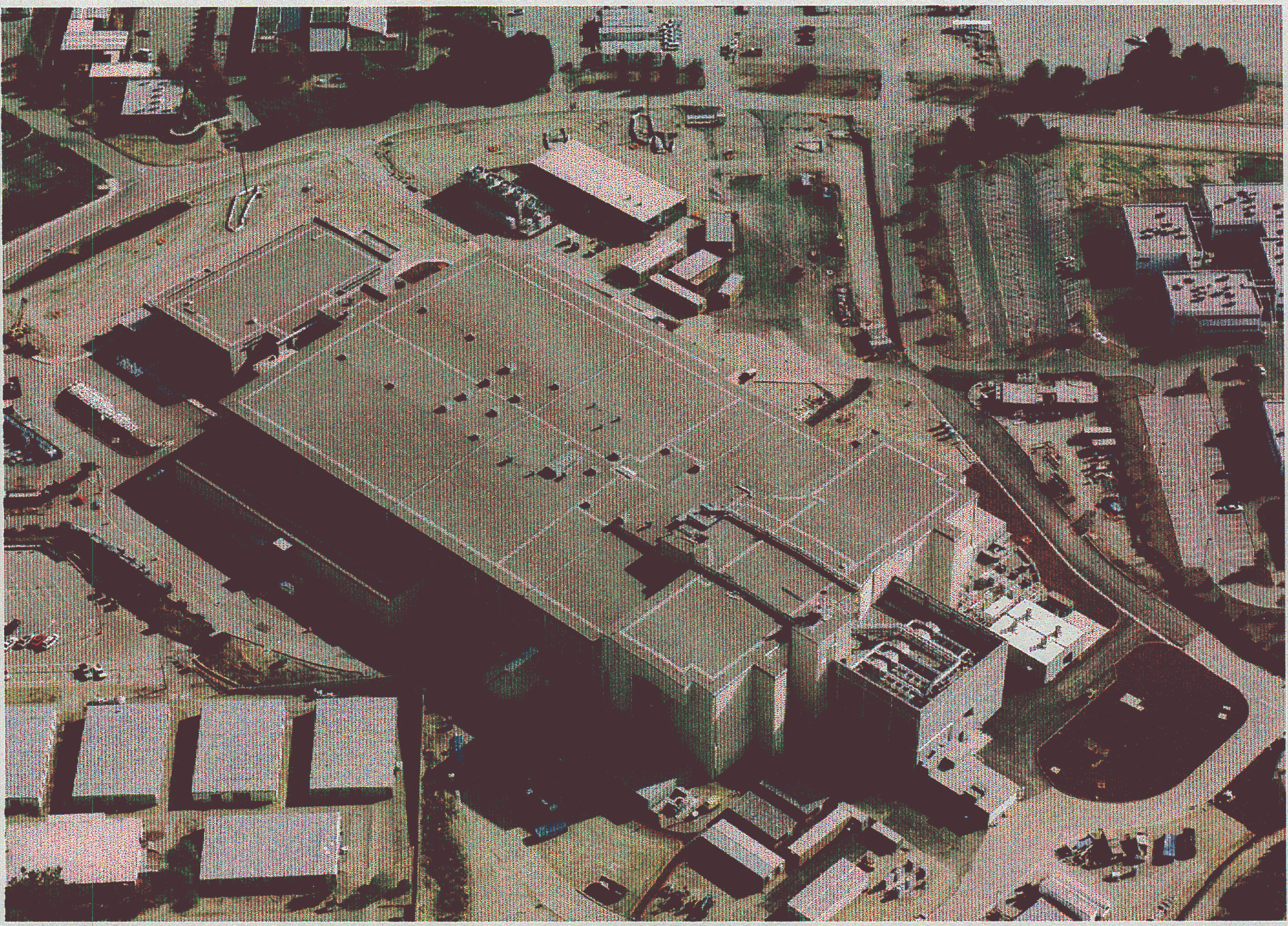

Fig. 5. Aerial photograph of the NIF site at Lawrence Livermore National Laboratory taken in October 2001 soon after the completion of the conventional facilities.

the installation and commissioning phase over the next few years. First light, which is defined as the first quad of four laser beams focused to target chamber center is scheduled for June 2004. Full completion of all 192 laser beams is scheduled for September 2008. However, in the time between first light and project completion, approximately 1500 experiments in support of the SSP, inertial confinement fusion, high- energy-density physics, weapons effects, inertial fusion energy, and basic science are planned to be performed.

After project completion, NIF is expected to provide approximately 750 shots per year for a wide variety of experimental users. Recently NIF was designated as a National User Facility with the support of the NNSA Office of Defense Programs. A National User Support Office is now being put in place to provide the necessary interface between the user communities and the national NIF Program. The first Director of NIF is Dr. George H. Miller, from LLNL, who also serves as the Associated Director for NIF Programs at LLNL.

IV. Conclusions and Future Directions

The National Ignition Facility has come a long way since the first DOE critical decision in January 1993 affirmed the need for NIF and authorized the conceptual design process. In that time NIF has met every scientific and technical challenge and is now in the final stages of design and construction prior to commencing installation of the 192 laser beams.

Research is also beginning on developing picosecond pulse capability on NIF to explore applications for high power x-ray backlighters, fast ignition concepts, and extreme field science. NIF's flexible, modular design allows a number of different technologies for pulse injection and final high power optics to be fielded and tested.

Rapid advances in the science of high-intensity laser-matter interactions have revealed new horizons for research. Related swift technological progress has also made possible the adaptation of high-energy lasers to generate pulses in the picosecond domain with powers exceeding one petawatt. There is a worldwide surge of scientific activity in this new field and it has become apparent that NIF has new potential for programmatic science requiring the generation of even higher energy petawatt (HEPW) pulses, 1-2 orders of magnitude beyond the 0.5 kJ of the first petawatt-class laser pioneered using the Nova Laser at LLNL. With a longer view, the available megajoule energy of NIF together with the amplification bandwidth of neodymium

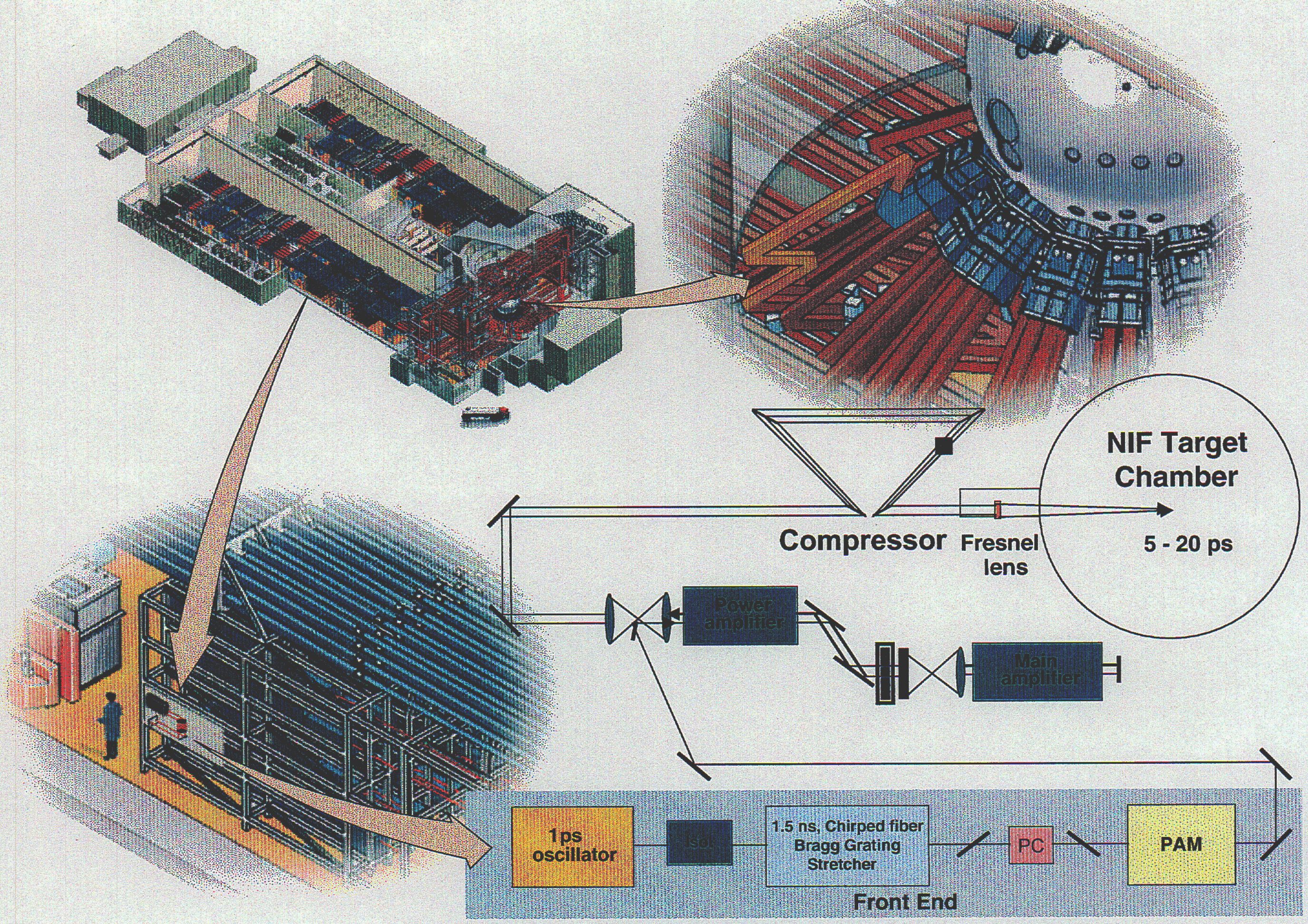

Fig. 6. Schematic representation of a short-pulse beamline concept for NIF. The front end is modified using a chirped fiber Bragg grating stretcher and a compressor utilizing thin transmission grating technology is placed in the beamline prior to the final apptics assembly at the target chamber. This concept provides 5-20 picosecond pulses corresponding to exawatt power levels in a single NIF beamline.

glass defines an ultimate power capability reaching the exawatt, or 1,000-petawatt level. A new Petawatt Initiative supported by National Nuclear Security Administration at the three main high energy laser facilities (LLNL, the Laboratory for Laser Energetics at the University of Rochester, and Sandia National Laboratories) seeks to exploit the potential of HEPW lasers and promises exciting new science for this National Program.

While full completion of all 192 laser beams is scheduled for September 2008, by 2004 this unique facility will already be providing the first glimpses of conditions heretofore only found in the most extreme environments imaginable under repeatable and well-characterized laboratory conditions for the benefit of national security and science.

Acknowledgments

The author would like to express his appreciation for the many people, institutions, and industrial partners that are diligently working to provide the National Ignition Facility for our nation. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

References

[1] For more information on the NIF Project please visit our web site at http://www.llnl.gov/nif